Evaluation of Alternative Network Preservation Strategies

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A study was conducted to evaluate the effects of underfunding on the total long-term cost of preserving networks. Many state highway agencies are experiencing both declining revenues and declining trunkline conditions. This decline raises the following question: Which alternative has the lowest total cost of preservation—allowing the network to decline from its current condition and later restoring it or maintaining its current condition? The pavement management system developed for the Michigan Department of Transportation is a network management system that includes the ability to evaluate the effects any given funding scheme has on the long-term (40-year) total cost of network preservation. Five funding schemes were analyzed for the preservation of two networks consisting of more than 11,000 lane-mi of pavement. A manual version of Michigan's network management system was used because it provides a simple means of illustrating how a network management system is used to control the long-term relationship between funding streams and network condition. Program costs were estimated on the basis of 3 years of historical project cost data. Five alternative funding schemes were evaluated, ranging from maintaining current condition to doing nothing for the first 10 years and then restoring the current condition. The study showed that the total agency cost over a 40-year analysis period can be highest when networks are maintained in current condition and lowest when they are allowed to deteriorate for 10 years before restoring and then maintaining current condition.

The long-term decline of the condition of many highway networks raises questions about future funding and revenue needs. It has long been held that timely maintenance and rehabilitation of networks will reduce their preservation cost and that inadequate funding would result in large increases in the future total cost of preserving networks compared with the cost of preservation. In an effort to study the long-term effects of various funding schemes, a study was conducted of the three Michigan Department of Transportation (MDOT) Highway Districts 5, 6, and 7, shown in Figure 1. The analysis methods are based on MDOT's network management system (*1*). Network management principles are based on the remaining service life (RSL) concept (*2*), network strategy analysis (*1,3,4*) and network life-cycle cost (LCC) (*5*). Actual district network performance and historical cost data are used for this study.

Analysis of alternative funding schemes is based on a manual computation version (*6*) of MDOT's network management system. Network performance bar charts are used to illustrate network condition and its rate of deterioration, and a simple cost matrix based on historical cost data is used to estimate the cost of alternative funding schemes.

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MDOT's application software system was used to obtain current network performance data. All other analysis products were manually computed in accordance with equations later explained. Typically, agency executives would need to evaluate alternatives in more detail than is presented in this paper. This can be accomplished within a reasonable time only by using application software designed for network management.

This paper is intended to illustrate how network management systems are used to evaluate alternative funding schemes before the preservation project and program development process, how they can simplify the process of allocating funds, and how there is economic advantage in placing network needs above the needs of individual projects.

BASIC NETWORK MANAGEMENT CONCEPTS

The performance of projects, networks, strategies, and programs is characterized by their lane-mile length and their average remaining service life (RSL). At the time of construction, the design service life (DSL) of projects and programs is the same as their RSL. Condition is considered to be poor or no longer acceptable when it deteriorates to an unacceptable level, referred to as the threshold value. The performance of networks is based on the RSL of the uniform sections that they consist of. The performance of programs is initially based on the DSL of the projects they consist of and later on the RSL of its projects. For networks, the sections of pavement of most concern are those in poor condition. They make up the majority of projects considered for annual programs. On the basis of remaining life methodology, Figure 2 illustrates the network deterioration process. The rehabilitation process simply moves projects from lower to higher RSL categories in accordance with their DSL. Network performance expressed in terms of RSL enables the use of an accounting process to keep track of the rate at which projects or uniform sections are deteriorating from each higher to each lower RSL category, the rate at which they are rehabilitated out of lower RSL categories, and to which higher RSL category the designers estimate of DSL would place them.

Relationship Between Network Performance, MR&R Programs, and MR&R Strategies

The condition of a network is simply the percentage of it that has an RSL of zero, which is the same as the percentage of network in poor or unacceptable condition. Network condition is a function of its rate of deterioration and the network

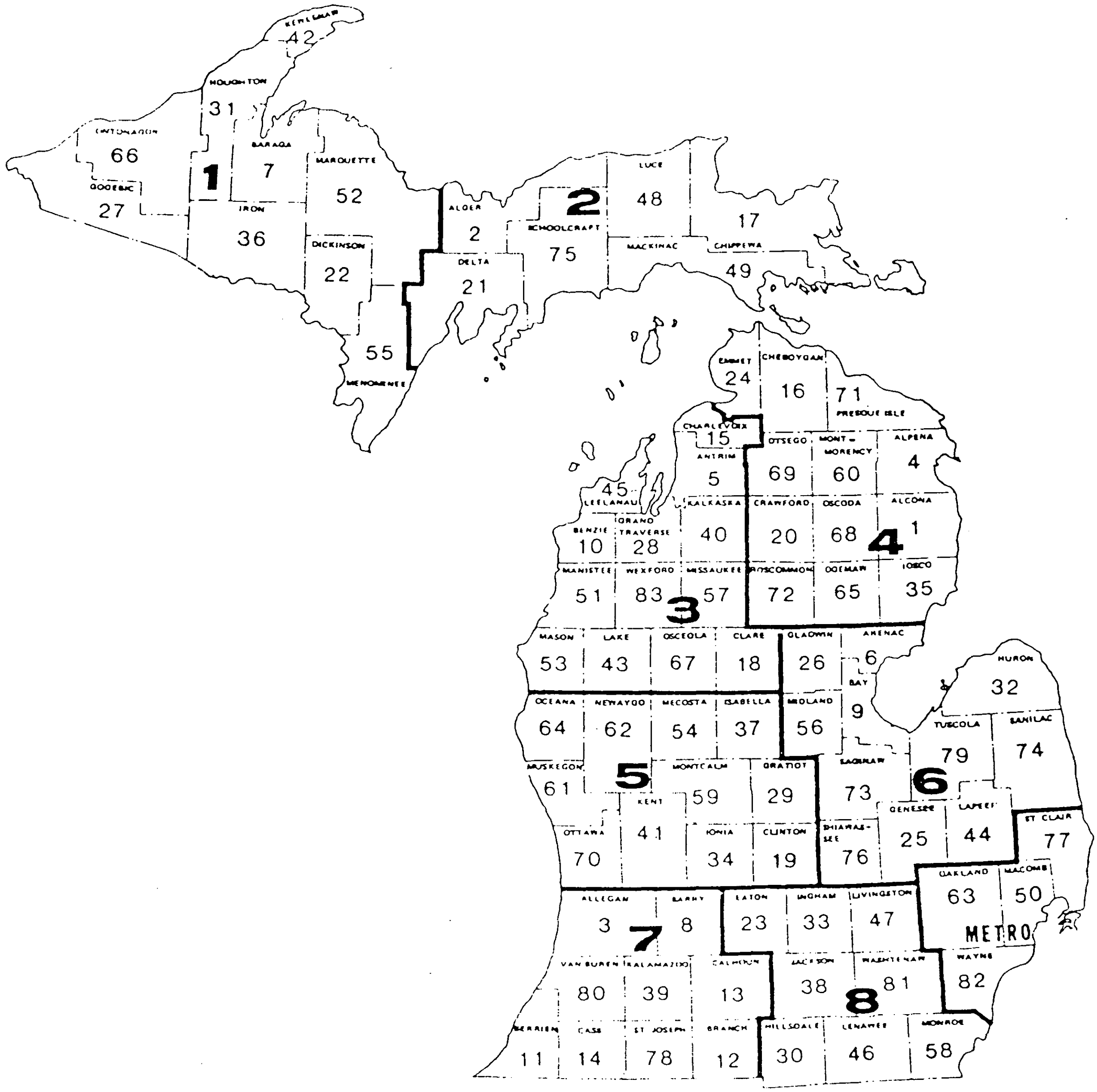

FIGURE 1 Map of Michigan showing locations of Districts 5, 6, and 7.

strategy used to preserve it. A maintenance, rehabilitation, and reconstruction (MR&R) strategy is defined as the percentage of network to be annually rehabilitated from each lower to each higher RSL category, and it is used as one of the MR&R program development constraints. For network management, it is beneficial to deal with network strategies rather than MR&R programs. This is so for two reasons: strategies eliminate the need to identify candidate projects, and the number of alternative funding schemes is not limited. For convenience, MR&R strategies can be generalized to the percentage of network annually preserved and its average DSL, in which case it is called a network strategy. The relationship between network condition (at equilibrium) and network strategy is as follows:

$$P_0 = 100 - (P \times \text{DSL}) \quad (1)$$

where P_0 is the network condition (percentage of network in the zero RSL category) and the annual MR&R strategy consists of P as the percentage of network annually preserved and DSL as the strategy's average design service life.

Equation 1 can be used to estimate the resulting condition of any network, given the MR&R strategy that is to be followed by annual MR&R programs.

The network's average RSL is calculated as follows:

$$\text{network RSL} = \sum X_i Y_i / 100 \quad (2)$$

where X_i is the RSL of the ith uniform section and Y_i is the percentage of network in the ith uniform section.

The products of Equations 1 and 2 were combined to form the chart shown in Figure 3. This chart relates resulting net-

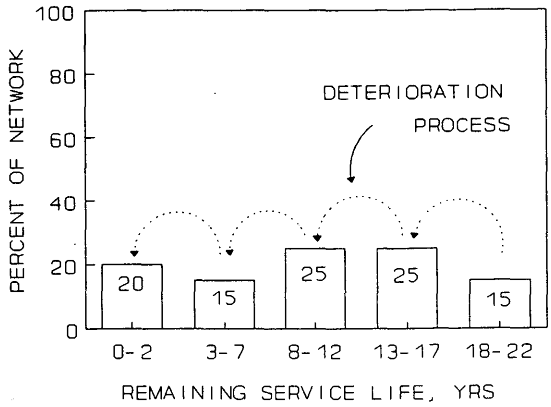

FIGURE 2 Network deterioration process.

work condition and RSL to the network strategies with which the MR&R program must comply. Its uses include the following:

- Given a network condition and RSL objective, what network strategy must each annual MR&R program comply with?
- Given a network strategy, what will the resulting network condition and RSL be?
- Given the desired network condition level, what RSL objective will maintain the desired condition level at lowest network LCC?

Cost of Alternative MR&R Programs

MR&R strategies provide the lane-mile lengths of projects to be designed into each RSL category. A simple cost matrix based on historical MR&R program cost data provides the relationship between average lane-mile cost of projects whose DSL is within each RSL category. The cost of alternative programs is the product of the lane-mile length of projects that the MR&R strategy requires to be designed into each RSL category and the corresponding cost per lane mile. Figure 4 is a simple cost matrix based on the average historical project cost data for District 5, 6, and 7 freeways and nonfreeways constructed from 1987 to 1989. Annual or 5-year MR&R program cost estimates are based on the strategy that would be used as a constraint for program development and the lane-mile cost data shown in Figure 4. Annual MR&R program cost estimates are based on the following equation:

$$\text{MR\&R program cost} = P/100 \times L \times C_x \quad (3)$$

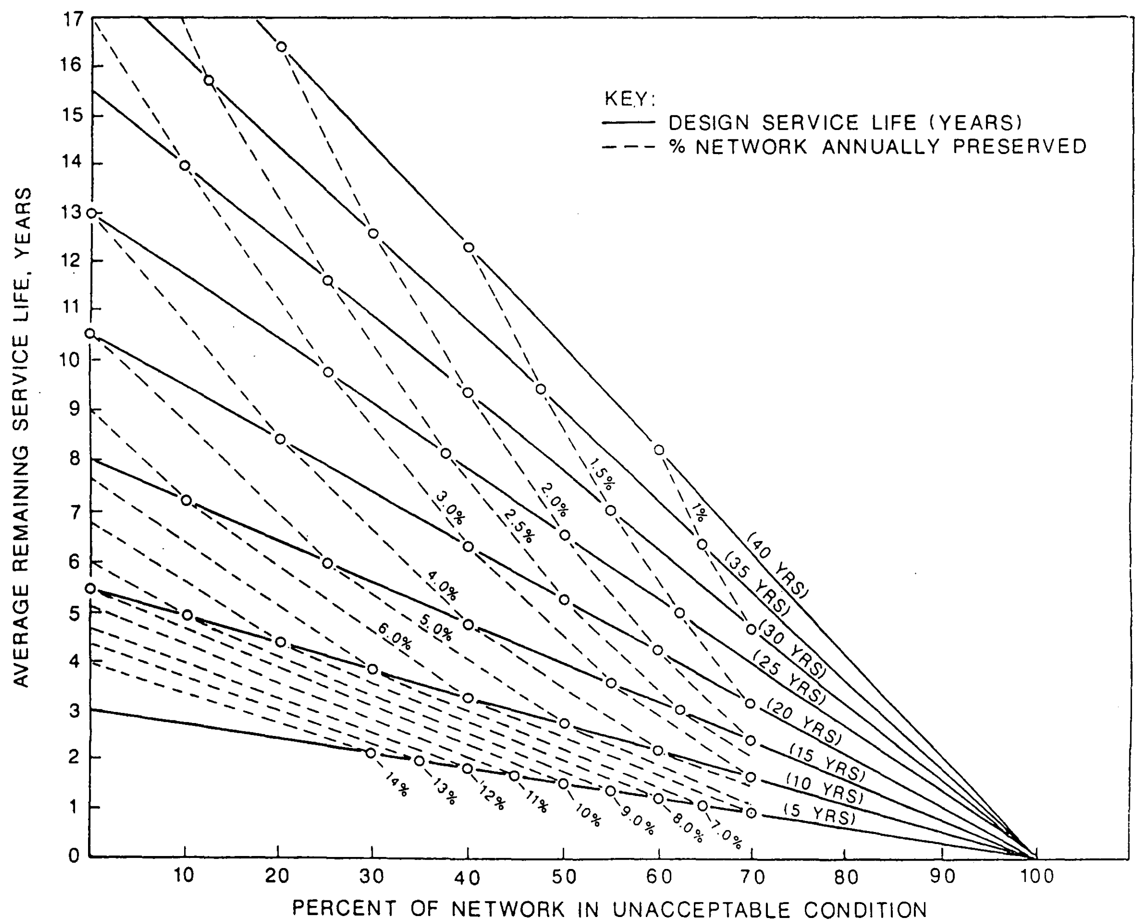

FIGURE 3 Network analysis chart relating alternative strategies (chart's interior) with which annual MR&R program must comply and resulting network condition and RSL.

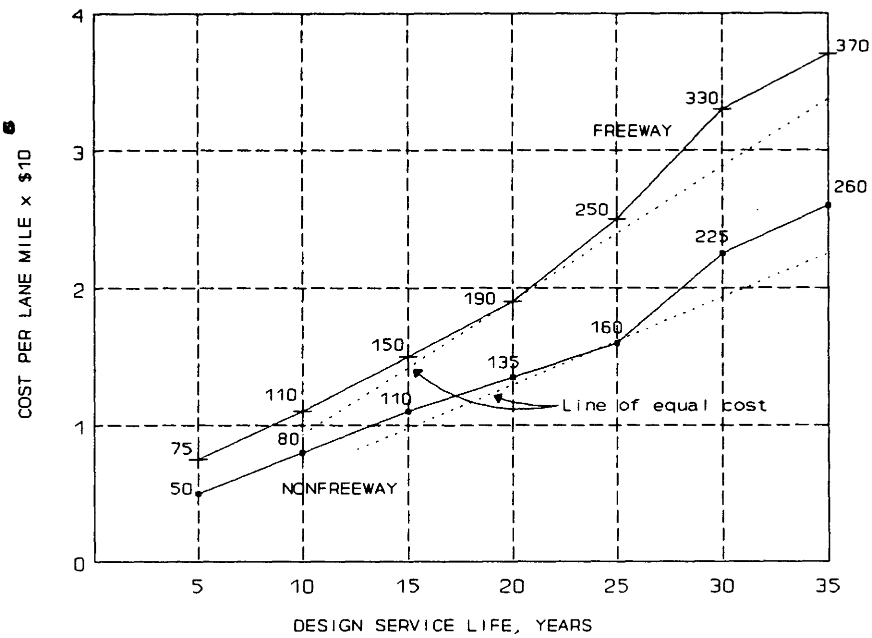

FIGURE 4 Simple cost matrix based on historical MR&R project cost data.

where L is the lane-mile length of the network, and C_x is the lane-mile cost of the DSL category corresponding to the program's DSL.

Reactive Maintenance Cost

The cost of reactive maintenance is based on procedures reported by Richardson (*7*). Simply, it is the product of the lane miles of pavement in unacceptable condition and the historical cost of reactive maintenance per lane mile of pavement in unacceptable condition. On the basis of 1989–1990 Michigan DOT maintenance cost data, the average cost of reactive maintenance for pavement in unacceptable condition is $1,200/lane-mi for nonfreeways and $4,600/lane-mi for freeways. Annual reactive maintenance cost (RMC) is computed on the basis of the following equation:

$$\$RMC = [P_0 + (P_5 - P)/2]/100 \times L \times C_x \qquad (4)$$

where P_5 is the percentage of network that annually deteriorates into the zero RSL category.

ECONOMIC ANALYSIS CONSIDERATIONS

Primary concerns when managing networks are knowing what minimum funding stream would be needed to maintain the desired condition and how this funding stream compares with anticipated revenues. The annual cost of a constant annual network strategy will be the same in 40 years as it is today, except as it is affected by the rate of inflation of construction costs. Agencies should consider this source of cost increase over time. For state highway agencies (SHAs), transportation revenues are largely a function of the relationship between the supply and demand for fuels, both of which are difficult to forecast and cannot be controlled.

Money is a productive resource, so there is a time value associated with its use. For SHAs, the difference between the earning power of money and the rate of construction cost inflation is considered the discount rate. Theoretically, it is reasoned, the cost of future investments should be discounted by an amount equal to the discount rate when compared with the cost of making the investment today. Discounting the value of money favors low-initial-cost alternatives and defers high-initial-cost investments. If decisions are made on the basis of the discounted value of money, the real cost of future pavement preservation programs will increase by an amount approximately equal to the rate of construction cost inflation plus the discount rate used to develop annual preservation programs (*8*). Therefore, the use of real today dollars is recommended because it presents a clearer picture of the relationship between revenues and funding streams and does not artificially increase the actual cost of future network preservation.

Typically, the selection of preservation treatments is based on which is best for the project or which has the lowest project LCC. The importance of the DSL of alternative treatments is unimportant except as it affects project LCC analysis. These methods of selecting treatments place project condition needs ahead of network condition needs and can result in the increased cost of network preservation (*5*). The basic idea is that at the project level, a 10-year DSL treatment does not have the same impact on the network as does a 20-year DSL treatment. The long-term impact of two projects with 10-year DSL treatments is equivalent to one project with a 20-year DSL, assuming all projects have the same lane-mile length. However, project LCC assumes that a string of short life treatments has the same impact on network condition as those having a longer life. This problem is created by thinking in terms of events (projects) rather than systems (networks), as discussed previously (*9*).

Economic analysis for preserving either projects or networks should include hundreds of alternative funding schemes, each of which is likely to have unequal costs and unequal benefits. This is the most complex configuration possible for economic analysis. Converting benefits to their dollar values and including the values in the project LCC analysis is a problem when considering benefits whose value is subjective or when their economic value is similar but their subjective value is not. The dollar value of benefits is difficult to estimate and of questionable accuracy and reliability. For this reason, the network management system developed for MDOT seeks to determine only the network strategy that will minimize the total long-term cost of network preservation given the target condition and RSL objectives. Benefits of alternative programs are addressed at the program development level by a program management system (*1,3,10*) whose objective is to maximize program benefits that have not been converted to dollar values.

This paper deals only with the network management perspective of economic analysis, that is, the relationship between the total cost of alternative 40-year strategies and the resulting network condition. For the sake of simplicity, no discount or inflation rate is considered. The cost of alternative funding schemes is expressed simply in terms of today dollars. The variable cost of reactive maintenance is included in the study.

TRUNKLINE SYSTEM PERFORMANCE DATA

The performance and lane-mile length of each district's networks are illustrated in bar chart form in Figure 5 for the nonfreeway and Figure 6 for the freeway. By use of manual pavement management system (PMS) analysis methods (*6*), all the products and information listed in the AASHTO guidelines for PMS (*11*) can be determined on the basis of the cost data shown in Figure 4, the average reactive maintenance cost per lane mile, the combined district pavement performance data, and the Figure 3 network analysis chart. For this paper, network condition and costs are determined on the basis of Equations 1 through 4. The Figure 3 network analysis chart can also be used to relate the target network condition (*X*-axis) and RSL (*Y*-axis) to the required network strategy by extending the *X*- and *Y*-values until they intersect. The point of intersection indicates the DSL and percentage of network values of the required network strategy.

FUNDING SCHEMES

Each of the five funding schemes listed in Table 1 is evaluated to determine the total cost of preservation—total cost being the cost of reactive maintenance plus the cost of the MR&R program for each of eight 5-year analysis periods. For simplicity, only the combined freeway and nonfreeway networks are analyzed using the funding schemes in Table 1.

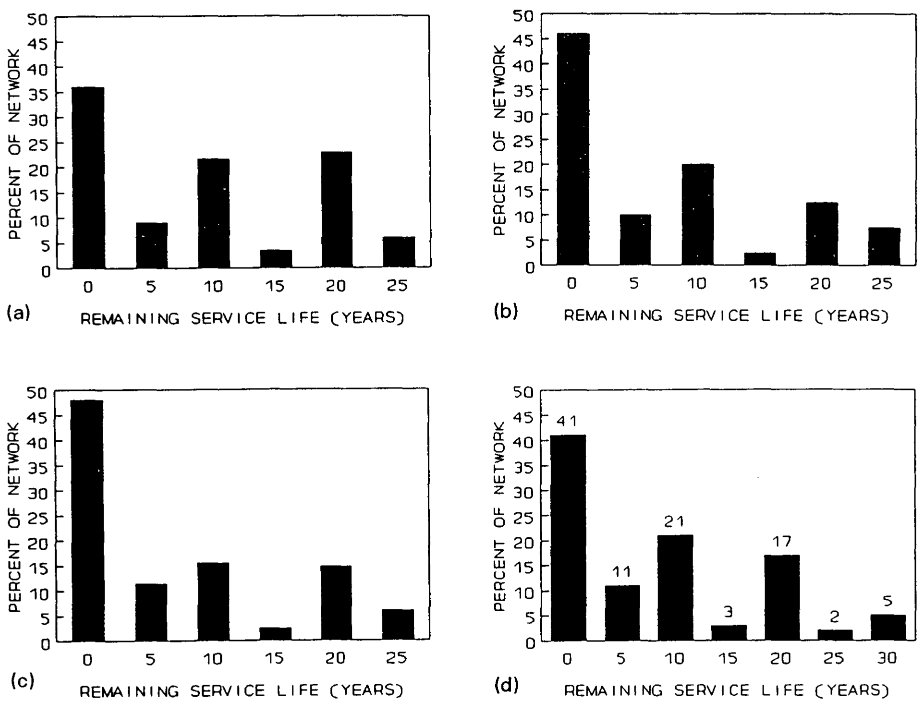

FIGURE 5 Current condition of nonfreeway networks: *a*, District 5, network length = 2,588 lane-mi; *b*, District 6, network length = 2,765 lane-mi; *c*, District 7, network length = 2,209 lane-mi; *d*, Districts 5 through 7, network length = 7,562 lane-mi, ARSL = 8.5.

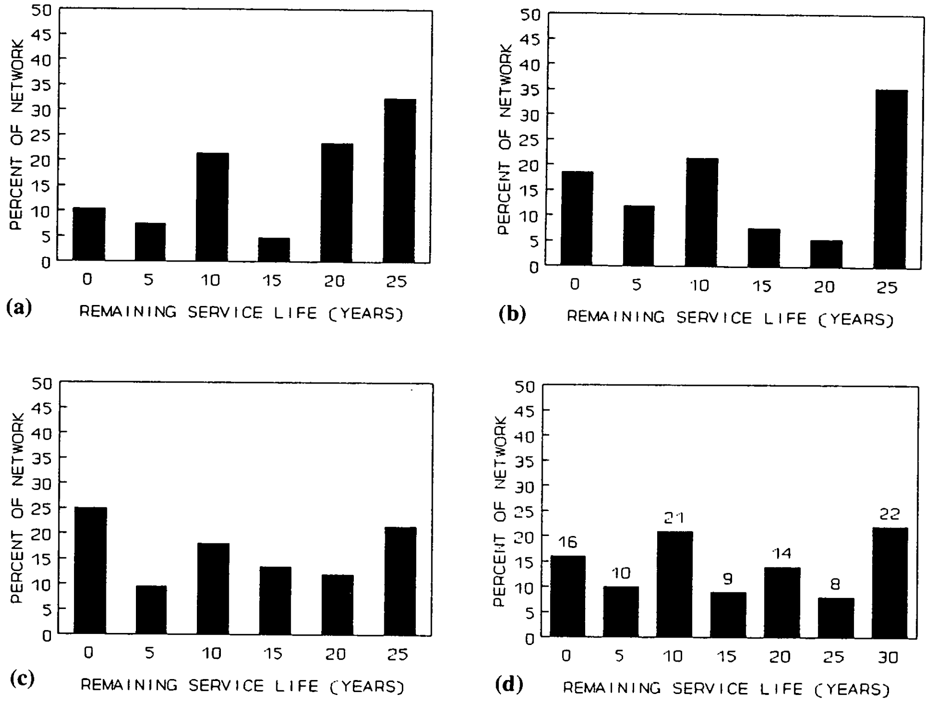

FIGURE 6 Current condition of freeway networks: *a*, District 5, network length = 1,343 lane-mi; *b*, District 6, network length = 1,152 lane-mi; *c*, District 7, network length = 1,253 lane-mi; *d*, Districts 5 through 7, network length = 3,748 lane-mi, ARSL = 15.3.

NETWORK LCC ANALYSIS

Analyses are based on the current condition status and RSL of each combined network (Figures 5*d* and 6*d*). Reactive maintenance cost is based on the percentage of network in the zero RSL category at the beginning of each 5-year period plus the percentage of network that deteriorates into it annually minus the percentage of network preserved into higher RSL categories (Equation 4). The MR&R strategy indicates the percentage of network that is to be preserved (moved or subtracted) from the zero RSL category and to what higher RSL category it is to be moved (added). The results explain what is done and present each calculation so as to illustrate methodology and results. Network LCC is simply the sum of the annual RMC and the annual MR&R program cost, over a 40-year analysis period, that is required to achieve and maintain a given network condition objective.

TABLE 1 Alternative Funding Schemes

Scheme Number	Action	Duration (years)
1	Do nothing but reactive maintenance	0–10
	Restore original condition	11–15
	Maintain original condition	16–40
2	Maintain original condition	0–40
3	Do nothing but reactive maintenance	0–10
	At least cost, restore and maintain original condition	11–40
4	Do nothing but reactive maintenance	0–10
	At least cost, eliminate all pavement in poor condition	11–40
5	At least cost, eliminate all pavement in poor condition	0–40

Scheme 1 Results

The condition of the networks after 10 years of doing nothing but reactive maintenance is shown in Figure 7*a* and *b*. Using the nonfreeway for an example, at the end of 10 years, the percentage of network in the zero RSL category is determined from Figure 5*d* data as the sum of the percentage of network in the following time periods: Period 0 (41 percent), Period 5 (11 percent), and Period 10 (21 percent) for a total of 73 percent. Computations necessary for determining total 40-year cost are listed to illustrate changes in cost and condition (P_0) over time.

The reactive maintenance cost for the first 10 years is as follows:

Nonfreeway

Period, $5[P_0 + (P_5 - P)/2]/100 \times L \times C_x =$ \$RMC
5 $[41 + (11 - 0)/2]/100 \times 7{,}562 \times \$1{,}200 = \$21{,}100{,}000$
10 $5[52 + (21 - 0)/2]/100 \times 7{,}562 \times \$1{,}200 = \underline{\$28{,}360{,}000}$
Total = \$49,460,000

Freeway

5 $[16 + (10 - 0)/2]/100 \times 3{,}748 \times \$4{,}600 = \$18{,}100{,}000$
10 $5[26 + (21 - 0)/2]/100 \times 3{,}748 \times \$4{,}600 = \underline{\$31{,}460{,}000}$
Total = \$49,560,000

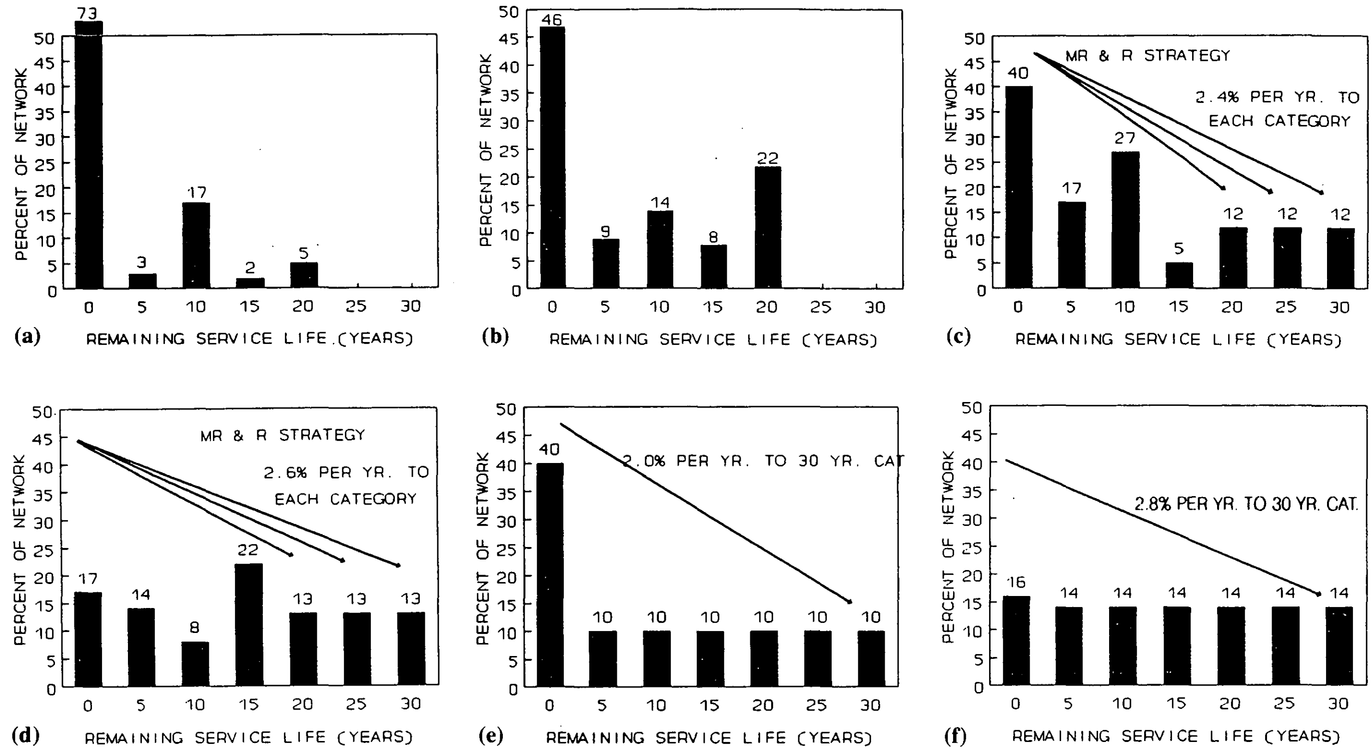

FIGURE 7 Condition of networks with *a*, after 10 years of do-nothing, ARLS = 3.2; *b*, after 10 years of do-nothing, ARLS = 7.6; *c*, 11 to 15 years of rapid preservation strategies, ARLS = 10.8; *d*, 11 to 15 years of rapid preservation strategies, ARLS = 14.6; *e*, 16 to 40 years of maintaining network condition with the preservation strategy shown, ARLS = 10.5; *f*, 16 to 40 years of maintaining network condition with the preservation strategy shown, ARLS = 14.7.

For Time Period 15, the MR&R strategy is to improve the network to its original condition. This means the percentage of network in the zero RSL category (unacceptable condition) must be reduced to the original level of 41 and 16 percent, respectively, for the nonfreeway and freeway networks. To do this the MR&R strategy (P) for the 5-year period must be equal to the percentage of network currently in the zero RSL category (P_0), as shown in Figures 7*a* and *b*, plus the percentage of network that will deteriorate into the zero RSL category in the 5-year period (P_5) minus the target percentage of the network that is to be in the zero RSL category (P_i) when the network's condition becomes stable:

$$P = P_0 + P_5 - P_i \tag{5}$$

The MR&R strategy (P) needed to restore the original condition of each network is as follows:

Network	$P_0 + P_5 - P_i = P$
Nonfreeway	73 + 3 − 41 = 35 percent
Freeway	47 + 9 − 16 = 40 percent

Based on Equation 4, the cost of reactive maintenance for Period 15 is as follows:

Nonfreeway
$5\,[73 + (3 - 35)/2]/100 \times 7{,}562 \times \$1{,}200 = \$25{,}860{,}000$

Freeway
$5\,[47 + (9 - 40)/2]/100 \times 3{,}748 \times \$4{,}600 = \$27{,}150{,}000$

The estimated cost of the MR&R program for Period 15 is based on the assumption that at the end of this period the 20-, 25-, and 30-year RSL categories would be void of pavements. Therefore, the strategy used is to fill each category with an equal percentage (length) of network. The selected MR&R strategy requires that at least 35 percent of the nonfreeway network be preserved, which, rounded up, would require rehabilitating 12 percent of the network into each category as shown in Figure 7*c*. This same procedure is used for the freeway network (Figure 7*d*). On this basis, the estimated MR&R program cost is as follows:

Nonfreeway

DSL	$P \times L \times C_i$ = MR&R cost
30	12 × 7,562 × \$225,000 = \$204,170,000
25	12 × 7,562 × \$160,000 = \$145,190,000
20	12 × 7,562 × \$135,000 = \$122,500,000
Total = \$471,860,000	

Freeway

30	13 × 3,748 × \$330,000 = \$160,790,000
25	13 × 3,748 × \$250,000 = \$121,810,000
20	13 × 3,748 × \$190,000 = \$92,580,000
Total = \$375,180,000	

For Periods 20 to 40, the MR&R strategy (P) that would maintain the restored network condition can be computed as follows:

$$P = (100 - P_0)/N \quad (6)$$

where N is the number of 5-year periods between the RSL category the pavements are improved to and the zero RSL category.

By assuming that the MR&R strategy will be to move pavements into the 30-year DSL category (the number of 5-year periods is 6), the 5-year MR&R strategy for each network is as follows:

Nonfreeway
$P = (100 - 41)/6 = 9.8$ percent or 10 percent

Freeway
$P = (100 - 16)/6 = 14$ percent

The resulting network performance would be as shown in Figures 7*e* and *f*. A strategy can be selected so as to change the network's RSL but not its condition. The strategy needed to maintain current network performance, including its current RSL, can be determined from Figure 3. From these strategies, the cost of reactive maintenance for each period from Periods 20 through 40 (five periods) is as follows:

Nonfreeway
Period $5[P_0 + (P_5 - P)/2]/100 \times L \times C_x$ = RMC
20 5[41 + (17 − 10)/2]/100 × 7,562 × $1,200 = $20,190,000
25 5[48 + (2 − 10)/2]/100 × 7,562 × $1,200 = $19,960,000
30 5[40 + (5 − 10)/2]/100 × 7,562 × $1,200 = $17,010,000
35 5[35 + (12 − 10)/2]/100 × 7,562 × $1,200 = $16,330,000
40 5[37 + (12 − 10)/2]/100 × 7,562 × $1,200 = $17,240,000
Total = $91,680,000

Freeway
20 5[16 + (14 − 14)/2]/100 × 3,748 × $4,600 = $13,790,000
25 5[16 + (8 − 14)/2]/100 × 3,748 × $4,600 = $11,210,000
30 5[10 + (22 − 14)/2]/100 × 3,748 × $4,600 = $12,070,000
35 5[18 + (13 − 14)/2]/100 × 3,748 × $4,600 = $15,090,000
40 5[17 + (13 − 14)/2]/100 × 3,748 × $4,600 = $14,220,000
Total = $66,380,000

The MR&R program cost for each 5-year period from Periods 20 to 40 (five periods) is as follows:

Nonfreeway
$P \times L \times C_{30}$ = MR&R cost
10 × 7,562 × $225,000 = $170,150,000
Period 20 to 40 cost = 5 periods × $170,150,000 = $850,750,000

Freeway
14 × 3,748 × $330,000 = $173,160,000
Period 20 to 40 cost = 5 periods × $173,160,000 = $865,800,000

Total 40-year cost for Preservation Scheme 1:

Nonfreeway
Period RMC + MR&R cost = total cost
5 and 10 $49,460,000 + $---------------- = $49,460,000
15 $25,860,000 + $471,860,000 = $497,720,000
20 to 40 $91,680,000 + $850,750,000 = $924,430,000
Totals $167,000,000 + $1,322,610,000 = $1,489,610,000

Freeway
5 and 10 $49,560,000 + $---------------- = $49,560,000
15 $27,150,000 + $375,180,000 = $402,330,000
20 to 40 $66,380,000 + $865,800,000 = $932,180,000
Totals $143,090,000 + $1,240,980,000 = $1,384,070,000

Figure 8*a* shows the network's condition over the 40-year analysis period.

Scheme 2 Results

To maintain the networks at their current condition, as shown in Figures 5*d* and 6*d*, the 5-year strategy (P) and DSL are, from Scheme 1, as follows:

Nonfreeway: P = 10 percent, DSL = 30 years.
Freeway: P = 14 percent, DSL = 25 years.

Total 40-year cost for preservation Scheme 2:

Network RMC + MR&R cost = total cost
Nonfreeway $163,110,000 + $1,361,200,000 = $1,524,310,000
Freeway $99,120,000 + $1,049,440,000 = $1,148,560,000
Totals $262,230,000 + $2,746,480,000 = $3,008,710,000

Figure 8*b* shows the network's condition over the 40-year analysis period.

Scheme 3 Results

The cost for the first 10 years is the same as the cost for Scheme 1. The least annual costs to restore and maintain the original condition based on Figure 4 costs are the 25-year DSL for the nonfreeway and the 20-year DSL for the freeway. The 5-year MR&R strategies needed to restore network conditions at least annual cost are as follows:

Nonfreeways $P = (100 - 41)/5 = 11.8$ percent or 12 percent
Freeways $P = (100 - 16)/4 = 21$ percent

Total 40-year cost for Preservation Scheme 3:

Network RMC + MR&R cost = total cost
Nonfreeway $203,950,000 + $871,140,000 = $1,075,090,000
Freeway $1,715,210,000 + $897,270,000 = $1,068,790,000
Totals $375,470,000 + $1,768,410,000 = $2,143,880,000

Figure 8*c* shows the network's condition over the 40-year analysis period.

Scheme 4 Results

The cost of doing nothing but reactive maintenance for Periods 5 and 10 is the same as that for Scheme 1. The least

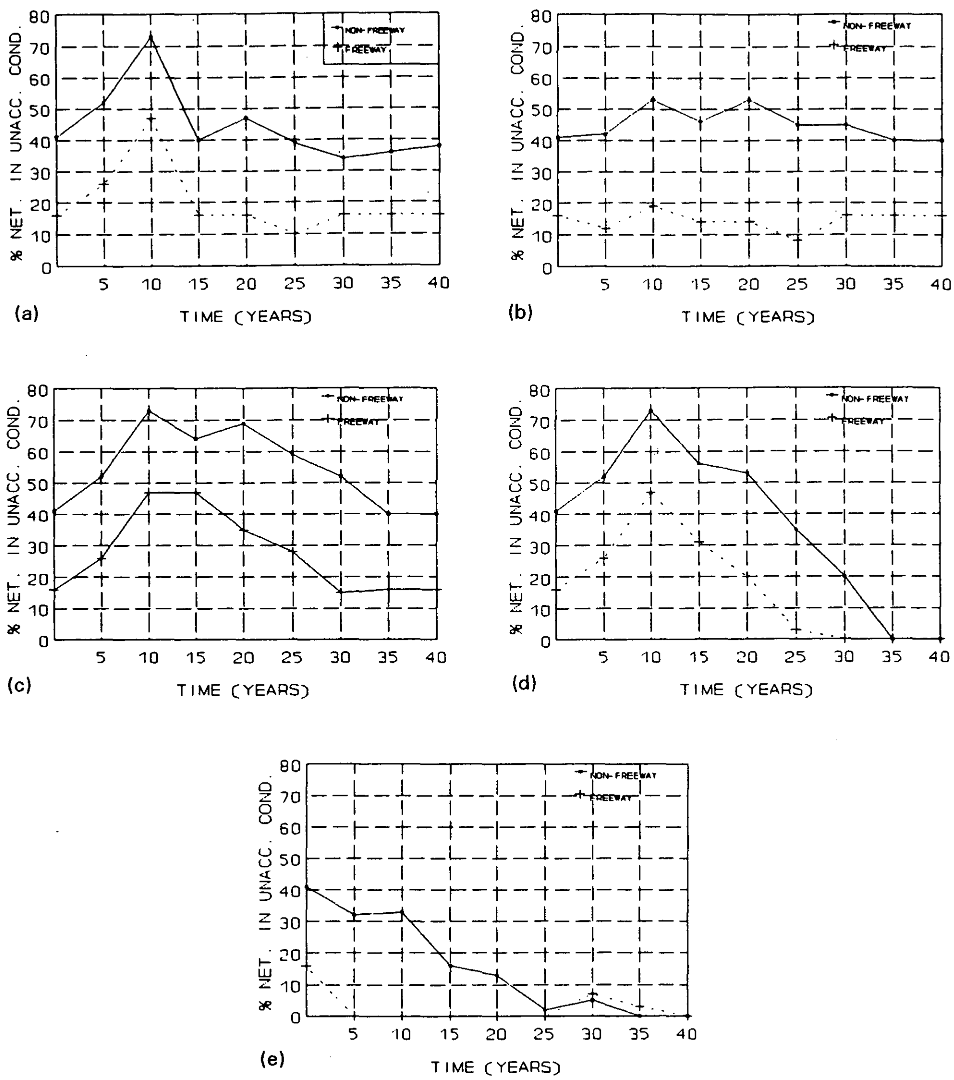

FIGURE 8 Change in network condition over 40-year analysis period as a result of funding schemes: *a*, Scheme 1; *b*, Scheme 2; *c*, Scheme 3; *d*, Scheme 4; *e*, Scheme 5.

annual cost to eliminate all pavements in unacceptable condition (0.0 percent of network in zero RSL category) would be to use the lowest lane-mile cost DSL for each network, which is the 25-year DSL for the nonfreeway and 20-year DSL for the freeway. The required 5-year MR&R straegies are as follows:

Nonfreeway P = (100 − 0)/5 = 20 percent (4 percent annually)
Freeway P = (100 − 0)/4 = 25 percent (5 percent annually)

Total 40-year network LCC for Preservation Scheme 4:

Network RMC + MR&R cost = total cost
Nonfreeway $140,430,000 + $1,451,900,000 = $1,592,330,000
Freeway $116,360,000 + $1,068,180,000 = $1,184,540,000
Totals $256,790,000 + $2,520,080,000 = $2,776,870,000

Figure 8*d* shows the network's condition over the 40-year analysis period.

Scheme 5 Results

The MR&R strategy for Scheme 5 would be the same as that for Scheme 4 except that it includes all eight 5-year periods. The 5-year MR&R program cost, based on Equation 3, for the 40-year analysis period is as follows:

Nonfreeway = $1,935,870,000
Freeway = $1,424,240,000

Total 40-year network LCC for Preservation Scheme 5:

Network RMC + MR&R cost = total cost
Nonfreeway $50,820,000 + $1,935,870,000 = $1,986,690,000
Freeway $7,330,000 + $1,424,240,000 = $1,431,570,000
Totals $58,150,000 + $3,360,110,000 = $3,418,260,000

Figure 8*e* shows the network's condition over the 40-year analysis period.

SUMMARY

The results of this study are presented in Table 2. Funding Scheme 1 reduces the cost of network preservation over that of Scheme 2. The cost of Scheme 2 is not the lowest-cost scheme for maintaining the current network condition; in addition, Scheme 1 does not generate as much agency savings as Scheme 3. Of Schemes 1 through 3, only Scheme 3 is a least-cost network strategy. These findings illustrate the following: (a) the cost of preserving networks does not have to be a function of the original network condition; (b) the cost of preserving networks at a given condition level is a function of the RSL at which it is maintained; and (c) Figure 4 indicates that the lowest-cost network strategy for preserving the network at any given condition level is when the DSL is 20 years for the freeway and 25 years for the nonfreeway.

Most of the greater cost of Scheme 4 compared with Scheme 3 and of Scheme 5 compared with Scheme 2 is attributed to the high cost of improving the heretofore neglected nonfreeway network. What is more significant is that the cost to improve the freeway network condition at least cost, Scheme 5, is essentially the same as that to maintain the current freeway condition with the Scheme 2 strategy. This illustrates how network management systems can be used to identify ways to improve network condition without increasing the funding level.

A do-nothing scheme should be a reasonable alternative in emergency situations and when declining revenues prevent maintaining target network condition levels. The duration of a do-nothing plan should be a function of rate of network deterioration, which is measured in terms of its RSL. Slowly deteriorating networks, characterized by large RSLs, can tolerate a longer period of do-nothing than can rapidly deteriorating networks. The impact on network condition of a 4-year do-nothing scheme if its RSL were 10 years is about the same as a 2-year do-nothing scheme if its RSL were 5 years. And somewhere in between do-nothing and full-funding (funding necessary to achieve target network condition objectives) alternatives are the conditions under which network management systems are most needed to learn how the economic efficiency of available funds can be improved.

More advantages and disadvantages of each funding scheme can be learned from Figure 8 and the data in Table 2 than are discussed. It is likely that decision makers would want to look even more deeply and at more alternatives. Because manual computations are too labor-intensive, this requirement is accomplished with a generic application software system that is surrounded with a utility software system designed to suit its users. The application software uses a comprehensive cost matrix (*1*) in place of the simple Figure 4 matrix. The advantages provided by the use of the software system are that it enables users to identify the network's patterns of behavior and underlying means by which preservation costs can be further reduced while maintaining condition objectives. The manual analysis methods used in this paper are not intended to be used to develop actual network strategies. And use of historical project cost data, like those shown in Figure 4, is not recommended to establish network strategies. MDOT's generalized or manual network management methods are intended to be used as training aides, for preliminary planning purposes, and as illustration of network management concepts.

For most agencies, timing of MR&R actions should be of economic importance only for pavements that are rapidly deteriorating and therefore will rapidly become a safety and reactive maintenance problem. However, timing can be of considerable economic importance to the users. And no economic justification can be found for maintaining pavements in good condition when only agency costs are considered. For agencies that do not yet have a good handle on user costs, the general practice is to subjectively set network condition objectives and then develop the lowest-cost programs necessary to achieve them. For condition objectives to be economically justified, they must include user as well as agency costs. That is, a pavement condition objective can be economically justified only when the annual agency-plus-user costs necessary to achieve network condition objectives are lower than the resulting agency-plus-user savings that are estimated to be derived from the annual preservation program. However, highway users seem to be willing to pay for good pavement serviceability whether or not they are economically justified. This subjective need for good pavement condition is similar to the choice between low-cost, low-comfort or high-cost, high-comfort automobiles. Hence, it is likely that condition objectives set for networks will be based on subjective as well as objective economic criteria.

TABLE 2 Performance and Total Cost of Funding Schemes 1 through 5

Scheme	Network	Network Performance(1) % Unacc.	ARSL(yrs)	Total Cost $ Billions
1	Non-Fr.	40	10.5	1.49
	Freeway	16	14.7	1.38 (2.87)
2	Non-Fr.	40	10.5	1.52
	Freeway	16	14.7	1.48 (3.00)
3	Non-Fr.	40	9.0	1.08
	Freeway	16	10.5	1.07 (2.15)
4	Non-Fr.	0	15.0	1.59
	Freeway	0	13.5	1.18 (2.77)
5	Non-Fr.	0	15.0	1.99
	Freeway	0	13.5	1.43 (3.42)

(1) Performance at the end of the 40 year analysis period.

CONCLUSIONS

This study demonstrates that the long-term performance of networks, when measured in terms of percentage of network in poor (unacceptable) conditions and RSL, is a function of only the network strategy (percentage of network and average DSL) with which the annual preservation programs comply. This approach is consistent with systems-thinking methodology: it is simple; it provides agencies with the ability to control budgets and network conditions over the long term, such as 40 years; it is compatible with any agency's project and program development process; and it facilitates communication among those representing political, managerial, and technical interests. Specific conclusions are as follows:

1. When managing networks, bar charts of the percentage of network in each 5-year remaining life category provide a

convenient means to communicate network patterns of behavior, condition status, and the effects of alternative funding schemes.

2. The cost of any alternative MR&R program can be estimated as the product of its lane-mile length and the historical cost per lane mile of projects having the program's average DSL.

3. The products and information in the AASHTO 1990 guidelines for PMS (*11*,pp.3–4) can be estimated on the basis of the data provided by the Figure 3 relationship between network performance and network strategies and the cost data provided by Figure 4.

4. The ultimate condition (percentage of network in poor condition) and RSL of any given network is dependent only on the lane-mile length and DSL (network strategy) with which the annual MR&R programs conform. This fundamental principle is based on the following assumptions: that the agency has the means to reliably estimate DSL of all feasible MR&R treatments, that actual pavement life correlates well with DSL estimates, and that the agency collects pavement condition data of sufficient detail to enable accurate identification of the boundaries and the RSL of all uniform sections that make up the designated network.

5. The cost to attain and then maintain any target network condition and RSL objective is dependent on the strategy that the annual MR&R programs must conform with and is independent of the network's original condition and RSL when the time required to reach the target condition level is not specified.

6. The diversion of funds from pavement preservation to other funding categories, such as Michigan has done with its District 5, 6, and 7 nonfreeway networks, is a reasonable method of meeting revenue shortfalls as long as the total agency-plus-user costs remain smaller than the total agency-plus-user savings derived from the annual preservation program.

7. The timing of network preservation should be more important for networks that rapidly deteriorate (low RSL) and least important when they slowly deteriorate (high RSL). For networks that have higher RSLs, such as those included in this study, timing of network preservation investments is not important.

8. Historical cost matrixes such as that shown in Figure 4 provide a simple means of identifying the approximate DSL of MR&R programs that should minimize preservation cost, and they provide a simple means to convey optimization concepts to nontechnical personnel.

9. It is often difficult to think in terms of preserving networks instead of projects. However, network management principles are simple, they provide the ability to improve economic efficiency, and they provide the relationship between any given funding level and the resulting network condition.

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